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DTRA-TR-12-74

TECHNICAL REPORT

Accelerated Decay of Radioisotopes

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January 2013

DTRA MIPR 11-2362

Joseph W. Schumer et al.

Prepared by:
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
00-01-2013

2. REPORT TYPE
Technical

3. DATES COVERED *(From - To)*
June 2011 – June 2012

4. TITLE AND SUBTITLE
Accelerated Decay of Radioisotopes

5a. CONTRACT NUMBER
DTRA MIPR 11-2362M

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
J.W. Schumer, B.V. Weber, J.C. Zier, J.P. Apruzese, J. Seely

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory, Code 6770
4555 Overlook Avenue SW
Washington, D.C. 20375

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Threat Reduction Agency
8725 John J. Kingman, STOP 6201
Ft. Belvoir, VA 22060-6201
J9BAS/S. Peiris

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
DTRA-TR-12-74

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Radioisotopes have energy densities up to1e9 J/g, whereas chemical-bonds typically store energies less than 1e4 J/g. Energy density is only a necessary condition for usefulness as an energetic material. Detailed here is the final report of a search for novel mechanisms for the rapid and controllable –release of nuclear energy within radioisotopes. In particular, the focus of this work was to theoretically, numerically, and experimentally quantify the cross-sections or nuclear reactions induced by heavy-ions or energetic neutrons. Radioisotopes were studied which are energy-rich (1e9 J/g) and are more abundant or naturally occurring with half –lives up to billions of years. The nuclear reaction cross sections were quantified by changes in the normal radioactive decay rate ("burn-up") or measuring the presence of a disturbed secular equilibrium ("enhanced secondary decay").

15. SUBJECT TERMS
Isotopes, Accelerators, Nuclear Physics, Warm dense matter

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	SAR	21	J.W. Schumer
Unclassified	Unclassified	Unclassified			19b. TELEPHONE NUMBER *(include area code)* (202) 404-4359

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ⟶ BY ⟶ TO GET

TO GET ⟵ BY ⟵ DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	$meter^2$ (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^{\circ}f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	$meter^3$ (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/$inch^2$ (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 ($N\text{-}s/m^2$)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/$foot^2$	4.788 026 x E -2	kilo pascal (kPa)
pound-force/$inch^2$ (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-$foot^2$ (moment of inertia)	4.214 011 x E -2	kilogram-$meter^2$ ($kg\text{-}m^2$)
pound-mass/$foot^3$	1.601 846 x E +1	kilogram-$meter^3$ (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

**The Gray (GY) is the SI unit of absorbed radiation.

"Accelerated decay of radioisotopes,"
Dr. J.W. Schumer, Naval Research Laboratory
MIPR# 11-2362M

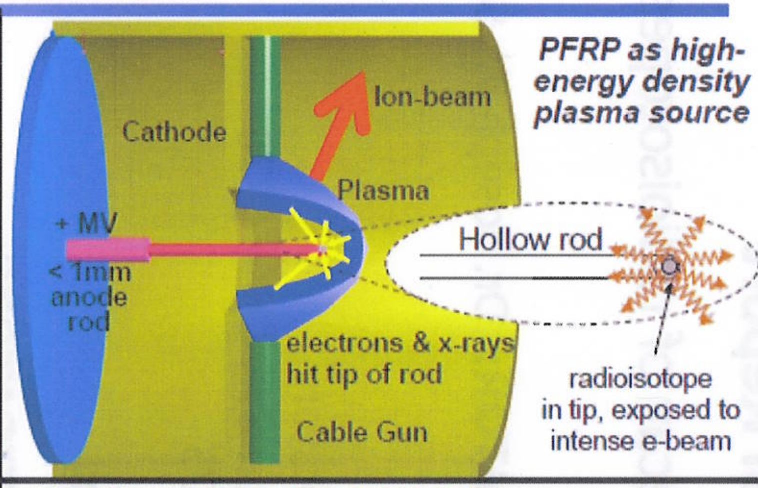
Description of effort:

Use neutron-inelastic scattering to induce effects on radioisotope decay-rate

Quantify potential of atomic x-rays to pump near-resonant nuclear transitions

Challenges:

- accurately quantifying atomic-nuclear coupling
- measurement of induced depletion following intense pulse irradiation
- controlling PFRP high-energy-density environment



Status of effort: Designing of PFRP experiments for controlled ionic species, analyzing results of recent neutron source development experiments, calculating expected reactions from (n,n'), awaiting approvals for radiation tests

Personnel Supported:

13 PhD-level scientists, with level-of-efforts ranging from few hours consultation to <20% level

Publications & Meetings:

2 published (RSI), 2 submitted (Phys. Plasma) papers

1 invited talk, 6 contributed talks

- **Year 1:** (30JUNE2011 – 30JUNE2012)
  - Measure K-line shift of ionized plasma using advanced x-ray spectrometer; design collective acceleration experiment
  - Develop pulsed neutron source with controllable energy and known fluence
- **Year 2:** (30JUNE2012 – 30JUNE2013), unfunded
  - Measure collective acceleration induced with PFRP diode
  - Expose energetic, long-lived isotope to neutron pulse to study depletion via (n,n') reaction
- **Funding Profile**

FY11 11-2362M	FY12	TOTAL
$350k	$0k	$350k

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"Accelerated Decay of Radioisotopes", MIPR 11-2362M Extension to "Potential of Electron-Beam Ionization for the Accelerated Decay of Radioisotopes" Proposal# BRCALL07-N-2-0047

Objectives:

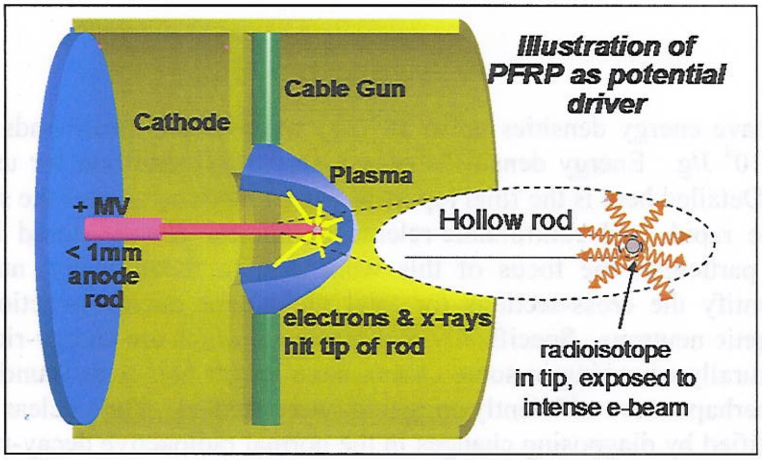
Radioisotopes have energy densities up to 10^9 J/g, whereas chemical-bonds typically store energies less than 10^4 J/g. Energy density is only a *necessary* condition for usefulness as an energetic material. Detailed here is the final report of work revolving around the search for novel mechanisms for the rapid- and controllable-release of nuclear energy stored in the form of radioisotopes. In particular, the focus of this work was to theoretically, numerically, and experimentally quantify the cross-sections (or total yields) for nuclear reactions induced by heavy-ions or energetic neutrons. Specifically, radioisotopes which are energy-rich (10^9 J/g), are more abundant (naturally-occurring in some cases), have longer half-lives (hundreds to billions of years), and are perhaps more efficiently triggered, were studied. The nuclear reaction cross-sections were quantified by diagnosing changes in the normal radioactive decay-rate ("burn-up") or measuring the presence of a disturbed secular equilibrium ("enhanced secondary decay"). This work was a one-year extension of work performed under MIPRs# 08-2468M, 09-2156M, and 10-2956M entitled "Potential of electron-beam ionization for the accelerated decay of radioisotopes" based on lessons learned and novel new findings.

Summary of Work:

Funding for this one-year effort was received in late May 2011, with a period of performance from 30 June 2011 – 30 June 2012. This final report details work performed in this year, as well as referencing the 3-year DTRA6.1 effort from which it was spawned. Proposed was a two-year continued study of the (1) high-energy-density plasma environment produced within the plasma-filled rod-pinch diode and (2) the utilization of a pulsed neutron source to study inelastic neutron scattering to accelerate the decay of radioisotopes. Due to funding constraints, only one year's effort was pursued. To these ends, the following tasks were completed within the first year of a planned two-year program:

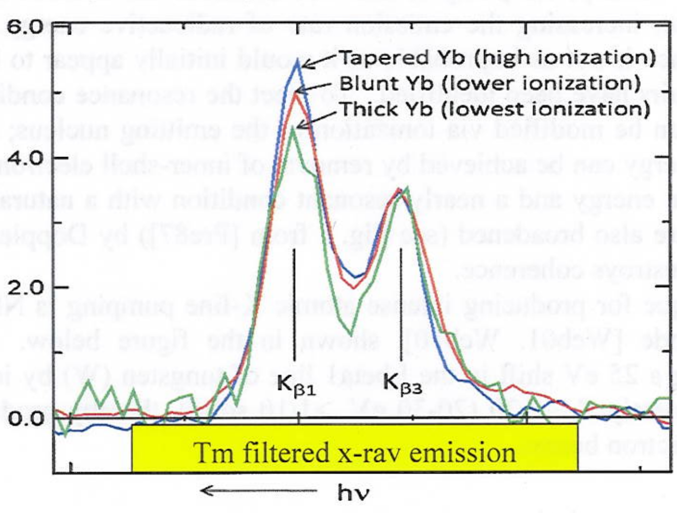
Task 1a (Atomic-nuclear resonance using PFRP plasma source): A potentially novel mechanism for nuclear pumping would employ an atomic-line resonantly matched in energy to the nuclear transition. Ideally, the pump K-line would induce the nucleus into a shorter-lived ground or excited state, increasing the emission rate of radioactive energy. The condition of atomic-nuclear resonance is not as improbable as it would initially appear to be, as a number of suitable atom-nuclei pairs have been identified. To meet the resonance condition, the atomic x-ray emission energy can be modified via ionization of the emitting nucleus; small (tens of eV) shifts in atomic line energy can be achieved by removal of inner-shell electrons [Sco78], causing an up-shift in transition energy and a nearly-resonant condition with a naturally-narrow nuclear transition. The lines are also broadened (see Fig. 3 from [Pre87]) by Doppler processes, which both aids overlap but destroys coherence.

A potential technique for producing intense atomic K-line pumping is NRL's plasma-filled rod pinch (PRFP) diode [Web01, Web10], shown in the figure below. In this year, we successfully measuring a 25 eV shift in the Lbeta1 line of tungsten (W) by ionizing near solid-density W to approximately Z ~ +20 (20-30 eV, >1/10 solid), thereby producing warm dense matter using intense electron beams.



Within the PFRP, high-power e-beams (500 kA, 1 MV, 50-ns) converge onto an mm-scale anode tip, generating a high-energy-density plasma (HEDP) environment (2.4 MJ/cm^3, 1.6 TPa, 25 eV in tungsten) and an intense source of x-rays. X-ray emission from this highly-ionized plasma is affected by the HEDP environment and may allow efficient coupling of an atomic x-ray to a nuclear transition. Detailed basic research into the HEDP environment was pursued under the first 3-years of this project; we improved the fielding of a new x-ray diagnostic [Per10, Sel10] and ascertained the amount of x-ray line-shifting that may be obtained from the PFRP diode and its HEDP environment. Additionally, the experimental results agreed with analytic and numerical calculations of the PFRP plasma. Future numerical studies to study the coupling between the HEDP and nuclear mechanisms were not completed, as these were planned for Year 2.

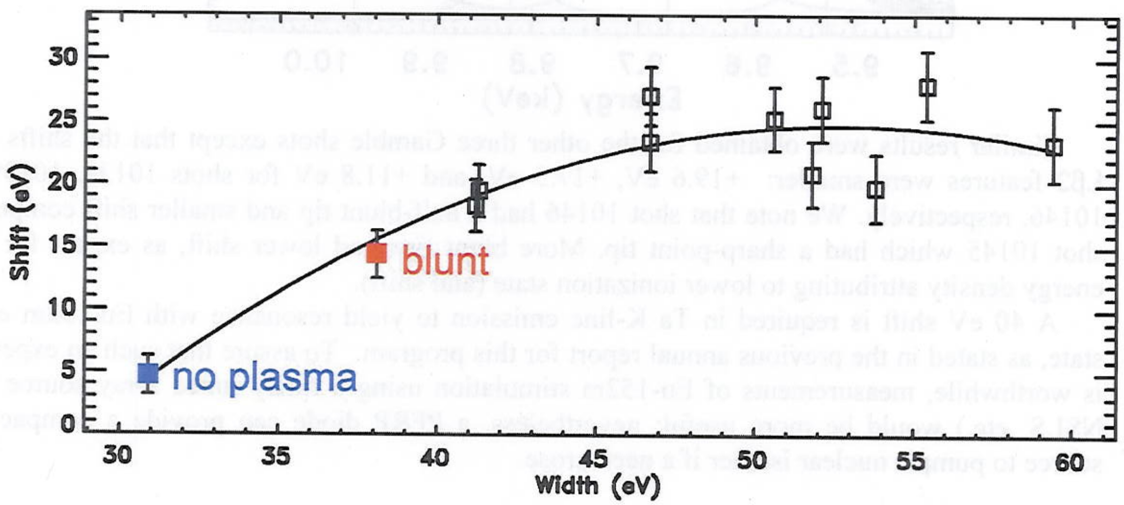
Experimental determination of the plasma and x-ray environments with a PFRP diode on Gamble II were continued, using a combination of diagnostics available within Code 6770 and Code 7674. Our efforts using K-edge filters to measure small shifts in Kalpha lines are described in two papers (PER12a and PER12b). Within the anode tip, iridium (Ir) was substituted for the tungsten (W) in the anode rod to take advantage of novel diagnostic technique developed for this program. Given that the K-edge of Lu (lutetium) filter would partially-absorb the Kalpha emission from the Ir rod if the x-rays coming from the hot iridium plasma were up-shifted as expected. Using this technique (details of which are the subject of refereed publication



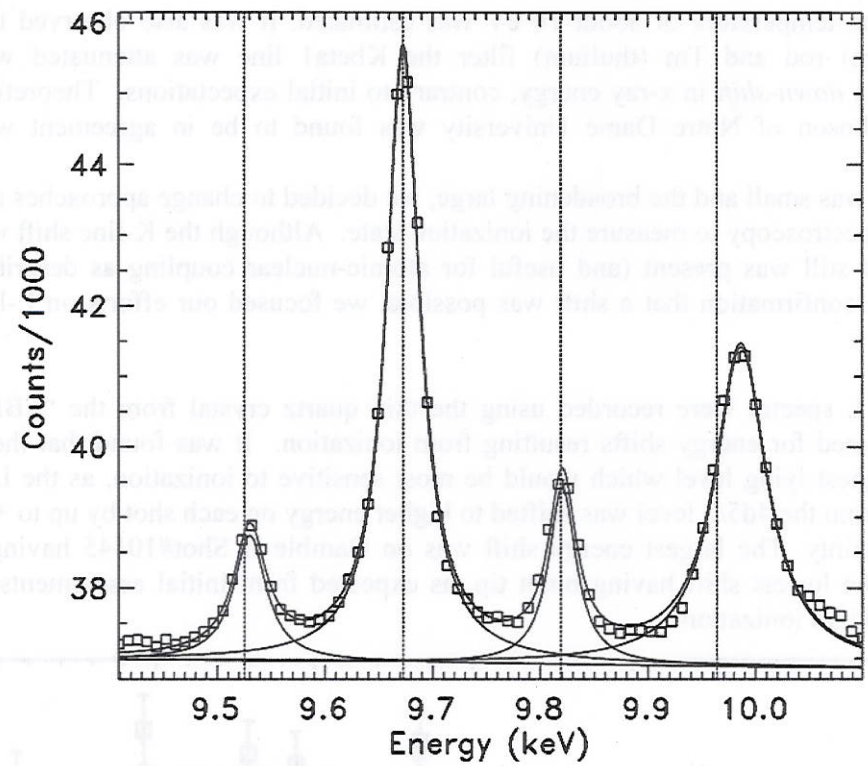
in draft now), a plasma temperature of about 16 eV was estimated. It was also observed that using a Yb (ytterbium) rod and Tm (thulium) filter the Kbeta1 line was attenuated with ionization as if due to a *down-shift* in x-ray energy, contrary to initial expectations. Theoretical work by Prof. W. Johnson of Notre Dame University was found to be in agreement with experiments.

As the K-line shift was small and the broadening large, we decided to change approaches and attempt to use L-line spectroscopy to measure the ionization state. Although the K-line shift was difficult to measure, it still was present (and useful for atomic-nuclear coupling as described above). To obtain the confirmation that a shift was possible, we focused our efforts on L-line spectroscopy.

The tungsten (W) L spectra were recorded using the thin quartz crystal from the "EBIT" spectrometer and analyzed for energy shifts resulting from ionization. It was found that the L transition from the highest lying level which would be most sensitive to ionization, as the Lβ2 transition at 9964 eV from the 4d5/2 level was shifted to higher energy on each shot by up to +28 eV with ±2 eV uncertainty. The largest energy shift was on Gamble II Shot#10145 having a sharp-point tip, with the lowest shift having blunt tip, as expected from initial assessments of energy density coupled into ionization.



The analysis of the spectrum from Gamble shot 10145, with the IP positioned near the RC, is shown below. The spectrum was summed and averaged in the vertical direction on the IP. The Lβ¬2 feature has a noticeable shift to higher energy. In the detailed spectrum, the shift of the Lβ¬2 feature from the 9964 eV tabulated energy is +22.0 eV; the average shift of the Lβ4, Lβ1, and Lβ3 transitions from the tabulated energies is 2.1 ± 2.5 eV. From the Table, the upper levels of these four transitions are Lβ4 (3p1/2), Lβ1 (3d3/2), Lβ3 (3p3/2), and Lβ2 (4d5/2). The Lβ2 transition is from the highest-lying level, is most sensitive to ionization, and has a significant shift to higher energy. The other three transitions are from lower lying levels, are less sensitive to ionization, and have no significant energy shift.



Similar results were obtained for the other three Gamble shots except that the shifts of the Lβ2 features were smaller: +19.6 eV, +17.5 eV, and +11.8 eV for shots 10138, 10139, and 10146, respectively. We note that shot 10146 had a half-blunt tip and smaller shift compared to shot 10145 which had a sharp-point tip. More blunt tips had lower shift, as expect for lower energy density attributing to lower ionization state (and shift).

A 40 eV shift is required in Ta K-line emission to yield resonance with Eu-152m excited state, as stated in the previous annual report for this program. To assure that such an experiment is worthwhile, measurements of Eu-152m stimulation using a finely tuned x-ray source (APS, NSLS, etc.) would be more useful; nevertheless, a PFRP diode can provide a compact light source to pump a nuclear isomer if a need arose.

Task 1b (Use of PFRP for "collective acceleration")

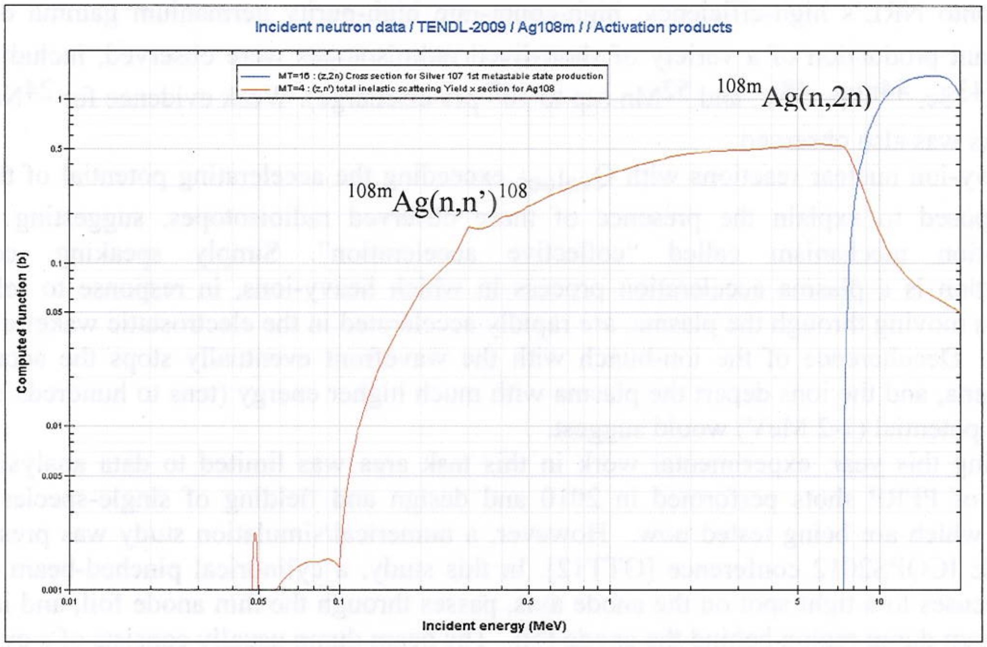
"Collective acceleration" processes driven by the PFRP diode were numerically studied, as this phenomenon was discovered under the initial 3-year basic research effort [Sch10]. Nuclear reactions in pulsed-power ion-diodes are usually induced by proton- or deuteron-projectiles accelerated to high energy by the voltage across the anode-cathode (A-K) gap. Reactions for which the incident projectile has a larger atomic number ($Z > 2$) are inhibited by the Coulomb barrier and are not usually detected. However, during the 3-year DTRA 6.1 effort, anomalous heavy-ion acceleration mechanisms induced nuclear reactions during the operation of a plasma-filled rod-pinch (PFRP) diode fielded on the 2-MV Gamble II generator, some of which the required an energy threshold (Q_{value}) larger than the diode potential difference. Products of these nuclear reactions were observed by measuring the gamma-ray energies and half-lives in witness plates (i.e. experimental hardware designed to survive the electrical discharge and neatly

mount onto NRL's high-efficiency, high-count-rate high-purity germanium gamma detector). Significant production of a variety of short-lived radioisotopes were observed, including ^{38}K, ^{34m}Cl, ^{43}Sc, ^{44m}Sc, ^{48}V, and ^{52}Mn (up to 10^8 per discharge). Weak evidence for ^{24}Na, ^{69}Ge, and ^{79}As was also observed.

Heavy-ion nuclear reactions with Q_{values} exceeding the accelerating potential of the diode are proposed to explain the presence of these observed radioisotopes, suggesting a novel acceleration mechanism called "collective acceleration". Simply speaking, collective acceleration is a plasma acceleration process in which heavy-ions, in response to relativistic electrons moving through the plasma, are rapidly accelerated in the electrostatic wakefield of the e-beam. Decoherence of the ion-bunch with the wavefront eventually stops the acceleration phenomena, and the ions depart the plasma with much higher energy (tens to hundreds of MeV) than the potential (1-2 MeV) would suggest.

During this year, experimental work in this task area was limited to data analysis of the handful of PFRP shots performed in 2010 and design and fielding of single-species plasma sources which are being tested now. However, a numerical/simulation study was presented at the IEEE ICOPS2012 conference [OTT12]. In this study, a cylindrical pinched-beam electron beam focuses to a tight spot on the anode axis, passes through the thin anode foil, and impinges into a beam dump region behind the anode foil. The beam dump usually consists of a cylindrical anode-can with roughly the same radius R as the diode and a depth L. Because of energy deposition from the intense electron beam, the interior surfaces of the anode-can are expected to be space-charge-limited emitters. Therefore the electron space charge in the anode-can will draw ions off these surfaces. As in the PFRP diode (which is a radially-convergent variant of this geometry), there is evidence of nuclear activation suggesting that ions are accelerated within this diode in excess of the diode voltage.

LSP particle-in-cell simulations were carried out to study the particle dynamics of the virtual cathode formation and to understand how some ions may be accelerated to high energy. It was found that if L is large compared to D, a virtual cathode forms in the anode-can, causing some electrons to return to the downstream endplate (anode foil). However, unstable field oscillations allow many electrons to move past the virtual cathode and propagate to the upstream endplate. Ions emitted from the interior surfaces of the anode-can are accelerated to high energy, providing partial charge- and current-neutralization of the electrons. Ions of approximately twice the diode accelerating voltage were produced in this geometry, with some ions exceeding that estimate if they surpassed the secondary virtual cathode. These would presumably be the source of the nuclear activation observed in various experiments. A paper detailing this work was recently submitted to Phys. Plasmas [RIC12].



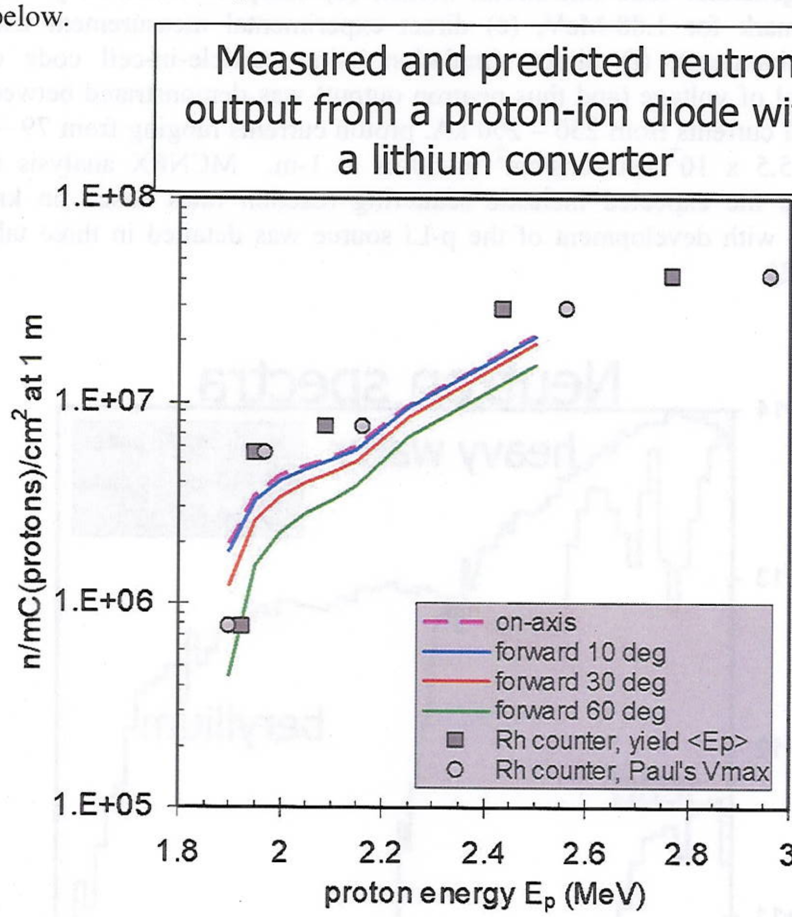
Task 2a (Development of intense pulsed neutron sources for (n,n') studies): The concept of exposing an energetic radioisotope to high-energy neutrons, potentially stimulating decay, was briefly studied. As the inelastic scattering (n,n') and high-energy (n,2n) reactions have reasonable cross-sections (up to a few barns) for neutron energies less than <20-MeV, these mechanisms were expected to be more fruitful than photon- or electron-based mechanisms. To study short-lived states induced by these neutrons, two sources of very intense, 0.1 - 10-MeV pulsed neutrons were demonstrated using the NRL Mercury generator at low-voltage (a 4-8 MV, 200-350 kA, 50-ns pulsed accelerator based on magnetically-insulated-transmission-line (MITL) with inductive voltage-adder (IVA) technology.

In September 2011, a low-energy neutron source was designed, developed, and fielded on Mercury based on the p-^{7}Li ion beam-solid target reaction. The p-^{7}Li is a convenient, controllable reaction providing neutrons of energies up to incident proton energy less the 1.9-MeV threshold, i.e. for a 2.4-MeV proton beam, a fairly-direction neutron source with energies up to 500-keV is generated. In December 2011, again using the Mercury generator but at the highest voltage (8-MV), a bremsstrahlung-based photoneutron source using a thick layer of heavy-water (D20) was designed and developed to produce a broad-band spectrum of neutrons up to 3 MeV. Details of both sources are below.

In late 2012, stimulated emission from energetic radioisotopes such as ^{108m}Ag, ^{150}Nd, and ^{176}Lu using broad-band neutron sources was planned to be experimentally studied. Due to long lead time to approve radiation safety protocols, only Lu-176 experiments were permitted. These neutron sources would have been very useful for studying the (n,n') reaction in ^{108m}Ag, producing a 2.4-min enhanced secondary decay with every depopulation. This is still planned for future work if funding allows. Details of this experiment are below.

High purity germanium (HPGe) gamma-ray diagnostics were used to quantify the induced activity and allow an estimate of reaction rate under this perturbing influence. The nuclear reaction cross-sections will be quantified by "burn-up" or "enhanced secondary decay". The

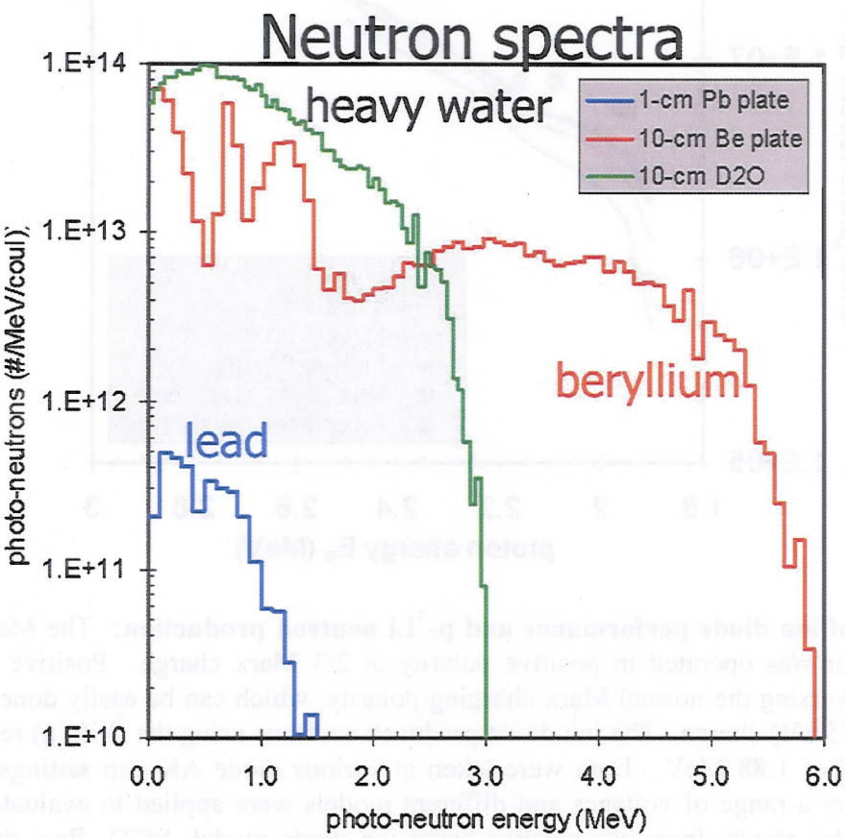
neutron energy spectrum needs to be controllable and varied to access reactions of interest (primarily (n,n') inelastic scattering). Theory and analysis using Monte Carlo codes (MCNPX) is still needed to benchmark to experimental data. Detailed results of the Lu activation experiment are shown below.



An overview of ion diode performance and p-^{7}Li neutron production: The Mercury pulsed power generator was operated in positive polarity at 2/3 Marx charge. Positive polarity was achieved by reversing the normal Marx charging polarity, which can be easily done at the lower 50 kV (out of 75 kV) charge. The ion diode produced neutrons using the ^{7}Li(p,n) reaction which has a threshold of 1.88 MeV. Data were taken at various diode AK gap settings to provided information over a range of voltages and different models were applied to evaluate the results. Analysis includes results from our pinched-beam ion diode model, MITL flow theory, circuit calculation to determine the Mercury load line, neutron yield calculations, and LSP simulations. Experimentally, the total/anode current I_a, the bound/cathode current I_c, and the ion current I_{ion} were measured using B-dot monitors, and the neutron yield was measured using rhodium activation counters and standardized bubble detectors.

Assessing the diode voltage was a key component of this experiment as the neutron spectrum and angular dependence is directly correlated to the ions with energies greater than 1.88-MeV. Normally, direct measurement of the voltage V in a high-voltage MITL is not possible, but measurement of I_a and I_c can be used to estimate V using MITL theory. However, with positive

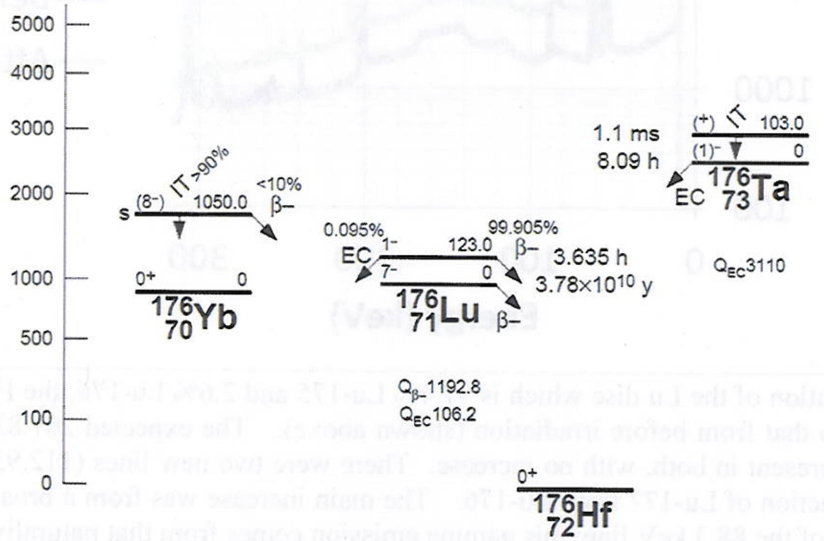
polarity layered MITL flow even this is problematic. Here, attempts to estimate the voltage were made in six ways: (a) assumed diode impedance scaling from pinched-beam ion diode model, (b) MITL theory, (c) generator load line/circuit model, (d) sharp-threshold of p-^{7}Li reaction as single-point benchmark for 1.88-MeV, (e) direct experimental measurement using vacuum voltmeter (in development), (f) direct simulation using particle-in-cell code called LSP. Experimental control of voltage (and thus neutron output) was demonstrated between 1.0 – 3.0 MV, producing total currents from 250 – 200 kA, proton currents ranging from 79 – 37 kA, and neutron fluxes up 5.5 x 10^7 neutrons/cm^2 in 50-ns at 1-m. MCNPX analysis needs to be performed to assess the expected inelastic scattering reaction rates based on known cross-sections. Progress with development of the p-Li source was detailed in three talks [OTT10, RUZ12, and MOS12].



Development of intense photoneutron production: To achieve higher-neutron energies with a modicum of spectral control, a novel intense pulsed photoneutron-based source was designed, tested, and characterized. As the Mercury generator can produce a high-intensity bremsstrahlung pulse (8-MeV, 200-kA, 50-ns yielding >750 rad(CaF_2) at 1 m) which, when attenuated by a thick medium containing nuclei with a low (γ,n) threshold, produced upwards of $>10^{12}$ neutrons in 50-ns with a survivable target allowing up to one shot per 10 minutes. Shown above are MCNP

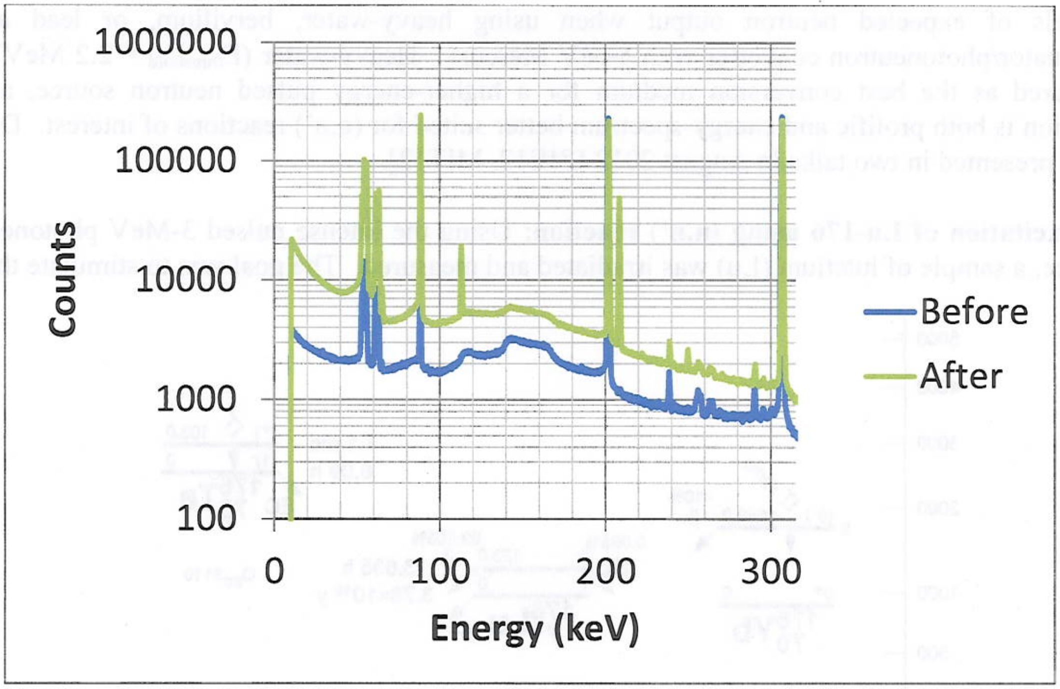
models of expected neutron output when using heavy-water, beryllium, or lead as an attenuator/photoneutron converter with 8-MV Mercury. Heavy-water ($E_{threshold}$ = 2.2 MeV) was procured as the best conversion medium for a higher-energy pulsed neutron source, as the reaction is both prolific and energy-spectrum better suited for (n,n') reactions of interest. Details were presented in two talks in August 2012 [ZIE12, MIT12].

De-excitation of Lu-176 using (n,n') reaction: Using the intense pulsed 3-MeV photoneutron source, a sample of lutetium (Lu) was irradiated and measured. The goal was to stimulate the



Energy levels relative to ^{176}Hf for elements with same mass number

long-lived (3.78e10 year half-life) ground state of Lu-176 into the isomer state of Lu-176m with a shorter half-life (3.635 hr) using neutrons and inelastic scattering (n,n') reaction. For each group of nuclei excited, the increased power output would be 1e14 times increase in power output. However, the conversion fraction would be expected to be many times less than unity.



Following irradiation of the Lu disc which is 97.4% Lu-175 and 2.6% Lu-176, the HPGe spectra was compared to that from before irradiation (shown above). The expected 201.83 and 306.78 keV lines were present in both, with no increase. There were two new lines (112.95 and 208.37 keV) from production of Lu-177 from Lu-176. The main increase was from a broad continuum and the increase of the 88.3 keV line; this gamma emission comes from that naturally existed Lu-176 but is only 13% of total yield as compared to 94% of 307 keV. The increase post-shot is 24x the 88.3 keV line (8.1e4 counts before, 1.9e6 counts after) in the 12-hour periods before and after the shot. Given exponential decay, approximately 2.1e8 isotopes of Lu-176m were generated via this experiment. A detailed analysis of this experiment will be documented in a future report.

DTRA relevance and potential applications - Many agencies within the Department of Defense (DoD) have recognized the need for advanced energetic materials (AEMs) and the required technologies to produce, control, and utilize them. AEMs include materials with nuclei in an excited state (radioisotopes) that may release this stored energy in a controllable and rapid fashion. These radioisotopes have energy densities on the order of 10^7 – 10^9 J/g, whereas chemical-bonds typically store energies around 10^3 – 10^4 J/g. Energy is released naturally as charged particles or photons via a long decay process, determining both power output and shelf-life of the medium. For example, radioisotopes have been used for decades as a long-lived energy storage medium, powering devices ranging from smoke-detectors to satellites. Energy density is necessary for compactness, but not sufficient for true usefulness in many scenarios. Of particular interest, however, is the ability to efficiently release this stored energy more quickly than the normal decay process, and on-demand.

Significance to the field - A variety of "accelerated depletion" techniques have been studied for the rapid release of stored nuclear energy, including the use of very intense, high-energy photon-, neutron-, and ion-beam sources. Unique to this study, however, is the consideration of a new-approach towards e-beam- and neutron-induced "triggering". The scope of this effort has been broadened to include other radioisotopes which are energy-rich (10^9 J/g), are more abundant (naturally-occurring in some cases), have longer half-lives (hundreds to billions of years), and are perhaps more efficiently triggered. Of particular interest are both "electron-capture" radioisotopes which are directly affected by their atomic electron environment and radioisotopes with low-lying excited states which may be stimulated by a "pump" of sub-100 keV x-ray line radiation or warm neutrons.

Research Highlights: Research highlights for the 2008 – 2010 program were detailed in previous reports. Based on the past 12-months of funded activity, we have focused on neutron source characterization tasks and measurement of WDM in the PFRP diode. Several papers and conference presentations were made under this project. In addition, four notable inclusions to this section are:

(1) Development of novel K-edge filtered x-ray spectrometer: although of limited utility as it requires a very subtle match between the rod material (e.g. Ir or Yb, in our case) and filter used over the image plate (e.g. Lu or Tm, in our case), the sensitivity of the technique cannot be called into question. With accurate knowledge of the x-ray line shapes, energy resolution down to a few eV for tens of keV x-rays is feasible. Work on this technique will continue, with a focus on continued theoretical support.

(2) Measurement of 25 eV Lbeta1 shift in W and corroboration with previous HEDP assessments of the PFRP diode using XRD for temperature, radiography for density, and L-shift for ionization state provides a wealth of benchmarked data for warm dense matter studies of high-Z materials.

(3) Demonstration of two intense pulsed neutron sources with controllable wide-band spectra: although the p-^{7}Li and gamma-D reactions are very well studied and no new physics is uncovered here, use of these reactions with precise characterization in a pulsed power environment is noteworthy. High-fluence warm and hot neutron sources become a useful research tools in their own right. The <50 ns bremsstrahlung pulse gives a neutron production rate >1e20 neutrons/s during each pulse.

(4) Production of Lu-176m isomer using intense pulsed neutrons was demonstrated. Approximately 2.1e8 isomers were generated from the ground state of Lu-176, and thereby transmuted to Hf-176 over ten hours. Stimulated decay using neutrons is more effective than that from electrons and photons in the experiments attempted thus far, but not efficient enough for DoD applications at present. Further research may be required.

Personnel Supported: A robust and diverse team of science professionals from various laboratories, universities, and industry have been assembled to support this effort, including:

Allen, Ray	NRL 6771	PhD. Electrical Engineering
Apruzese, John (PI)	NRL 6771/L3 Communications	PhD. Astrophysics
Boyer, Craig	NRL 6777/L3 Communications	PhD. Physics
Hinshelwood, David	NRL 6773	PhD. Physics
Jackson, Stuart	NRL 6773	PhD Physics
Mosher, David	NRL 6771/L3 Communications	PhD Physics
Ottinger, Paul	NRL 6771/L3 Communications	PhD Physics
Pereira, Nino	ARL/EcoPulse	PhD Physics
Schumer, Joseph (PI)	NRL 6770	PhD Nuclear Engineering
Seely, John (PI)	NRL 7674	PhD Physics
Weber, Bruce (PI)	NRL 6773	PhD Physics
Young, Frank	NRL 6773/L3 Communications	PhD Nuclear Physics
Zier, Jacob	NRL 6771	PhD Nuclear Engineering

All members of this team worked part-time on this project (at most 20% FTE) with allowance of synergism with other projects for scheduled machine operations, diagnostics support, and computational modeling set-up successfully leveraged.

Publications & Technical Reports:

[PER12b] "Near-coincident K-line and K-edge energies as ionization diagnostics for some high atomic number plasmas," N.R. Pereira, B.V. Weber, D.G. Phipps, J.W. Schumer, J.F. Seely, J.J. Carroll, J.R. Vanhoy, K. Slabkowska, and M. Polasik, *submitted to Physics of Plasmas*, 2012.

[RIC12] "Acceleration of ions by an electron beam injected into a closed conducting cavity," A.S. Richardson, P.F. Ottinger, S.B. Swanekamp, and J.W. Schumer, *submitted to Physics of Plasmas*, 2012.

[PER12a] "~10 eV ionization shift in Ir Kalpha2 from a near-coincident Lu K-edge," N.R. Pereira, B.V. Weber, D. Phipps, J.W. Schumer, J.F. Seely, J.J. Carroll, J.R. VanHoy, K. Slabkowska, and M. Polasik, Rev. Sci. Instrum. **83**, 10E110, 2012.

[PER10a] "K-line spectra from tungsten heated by an intense pulsed electron beam," N.R. Pereira, B.V. Weber, J.P. Apruzese, J.W. Schumer, J.F. Seely, C.I. Szabo, C.N. Boyer, D. Mosher, S.J. Stephanakis, and L.T. Hudson, Rev. Sci. Instrum. **81** 10E302, 2010.

[SEL10b] "Spatial resolution of a hard x-ray CCD detector," John F. Seely, Nino R. Pereira, Bruce V. Weber, Joseph W. Schumer, John P. Apruzese, Lawrence T. Hudson, Csilla I. Szabo, Craig N. Boyer, and Scott Skirlo, Applied Optics **49** (23), 10 August 2010.

[SEL10a] "Lateral propagation of MeV electrons generated by femtosecond laser irradiation," J. F. Seely, C. I. Szabo, P. Audebert, E. Brambrink, E. Tabakhoff, and L. T. Hudson, Phys. Plasmas **17**, 023102, 2010.

[LIT10] "Anomalous fluorescence line intensity in megavoltage bremsstrahlung," M.S. Litz, G. Merkel, N.R. Pereira, C.N. Boyer, G.E. Holland, J. W. Schumer, J.F. Seely, L.T. Hudson, and J.J. Carroll, Phys. Plasmas **17**, 043302, 2010.

[SEM09] "Front and back side processed unintentionally doped GaAs Schottky detectors for X-ray detection," F. Semendy, S. Singh, M. Litz, P. Wijewarnasuriya, K. Blaine, N.Dhar, Solid-State Electronics, Oct 2009.

[MOS09] "X-Ray Absorption and Scattering Issues for Rod-Pinch Radiographic Sources," D. Mosher, D.D. Hinshelwood, G. Cooperstein, B. Huhman, R.J. Allen, S.S. Lutz, M.J. Berninger, B.V. Oliver, S. Portillo, and T. Haines, in the Proceedings of the 2009 IEEE Pulsed Power Conference (Washington, DC, June 2009).

[APR09] "Feasibility of Self-Sustained Stimulated Excitation and Decay of Radioisotopes by Resonant Atomic K_{alpha} Radiation in a Two-Element Medium", J. P. Apruzese and J. W. Schumer, Pulsed Power Physics Branch Technote No. 2009-04, 3 March 2009.

[FER09] "Megavoltage bremsstrahlung end point voltage diagnostic," T. Feroli, M.S. Litz, G. Merkel, T. Smith, N. Pereira, J. Carroll, Rev. Sci. Instr. **80** (3), 034301, March 2009.

[WEB08a] "Radiographic Properties of Plasma-Filled Rod-Pinch Diodes," B.V. Weber, R.J. Allen, R.J. Commisso, G. Cooperstein, D.D. Hinshelwood, D. Mosher, D.P. Murphy, P.F. Ottinger, D.G. Phipps, J.W. Schumer, S.J. Stephanakis, S.B. Swanekamp, S. Pope, J. Threadgold, L. Biddle, S. Clough, A. Jones, M. Sinclair, D. Swatton, and T. Carden, IEEE Trans. Plasma Sci. 36, 443 (2008).

Interactions/Transitions:

a) *Participation/presentations at meetings, conferences, seminars, etc.*:

[SEE12] "Tungsten L Transition Line Shapes and Energy Shifts Resulting from Ionization in Warm Dense Plasmas," John Seely, Bruce Weber, David Phipps, Nino Pereira, Uri Feldman, Lawrence Hudson, and Joseph Schumer, 16th International Workshop on Radiative Properties of Hot Dense Matter (RPHDM, Santa Barbara, CA), 5-9 November 2012.

[ZIE12] "Characterization of an Intense Pulsed Photoneutron Source for Active Detection," J.C. Zier, R.J. Allen, J.P. Apruzese, R.J. Commisso, D.D. Hinshelwood, A.L. Hutcheson, S.L. Jackson, L.J. Mitchell, D. Mosher, D.P. Murphy, D.G. Phipps, B.F. Phlips, J.W. Schumer, S.B. Swanekamp, R.S. Woolf, E.A. Wulf, and F.C. Young. *2012 Conference on the Application of Accelerators in Research and Industry (CAARI)* (2012), invited.

[MIT12] "Measurements of Neutron Fluence from a Secondary Neutron Converter Irradiated with an 8 MeV Bremsstrahlung Pulsed Power Accelerator Beam," L.J. Mitchell, A.L. Hutcheson, B.F. Phlips, E.A. Wulf, C.S. Gwon, J.C. Zier, S.L. Jackson, J.W. Schumer, R.J.

Commisso, R.S. Woolf, F.C. Young, and L. Jackson. *2012 Conference on the Application of Accelerators in Research and Industry (CAARI)* (2012).

[MOS12] "Prompt Sub-MeV Neutron Production from the 7Li(p,n)7Be Reaction on Mercury," D. Mosher, J.P. Apruzese, R.J. Commisso, D.D. Hinshelwood, S.L. Jackson, J.W. Schumer, F.C. Young, J.C. Zier, J. O'Malley, C. Clemett, M. Ellis, P.N. Martin, A. Thandi, J.R. Threadgold, L. Hutcheson, L.J. Mitchell, B.F. Phlips, R.S. Woolf, and E.A. Wulf. *2012 IEEE International Conference on Plasma Science* (Edinburgh, UK, July 2012).

[OTT12] "Virtual Cathode Ion Acceleration behind the Anode Foil of a Pinched-Beam Ion Diode," P.F. Ottinger, A.S. Richardson, S.B. Swanekamp, and J.W. Schumer. *2012 IEEE International Conference on Plasma Science* (Edinburgh, UK, July 2012).

[PER12] "Near-coincident K-line and K-edge energies as ionization diagnostic for some high atomic number plasmas," N.R. Pereira, B.V. Weber, D.G. Phipps, J.W. Schumer, J. Vanhoy, J.J. Carroll, and M. Polasik. *19th Topical Conference High-Temperature Plasma Diagnostics* (2012).

[RUB12] "Modelling of the 7Li(p,n)7Be Neutron Yield from Mercury using GEANT-4 and LSP," M. Rubery, J. Threadgold, J. O'Malley, C. Clemett, M. Ellis, P.N. Martin, A. Thandi, J.C. Zier, S.L. Jackson, D.D. Hinshelwood, D. Mosher, R.J. Allen, J.P. Apruzese, R.J. Commisso, D.G. Phipps D.P. Murphy, J.W. Schumer, B.V. Weber, F.C. Young, A. Hutchinson, L. Mitchell, B. Phlips, E. Wulf, and R. Woolf. *2012 IEEE International Conference on Plasma Science* (Edinburgh, UK, July 2012).

[SCH10a] "Evidence of Heavy-Ion Reactions from Intense Pulsed Warm, Dense Plasmas," J.W. Schumer, F.C. Young, B.V. Weber, S.L. Jackson, C.N. Boyer, D. Mosher, and S.J. Stephanakis, 2010 IEEE International Conference on Plasma Science (Norfolk, VA, June 2010), p. 384 and 2010 CAARI (Ft. Worth, TX, August 2010).

[WEB10] "K-Shell Spectra of Warm, Dense Plasmas Produced by Intense Pulsed Electron Beams," B.V. Weber, J.P. Apruzese, C.N. Boyer, D. Mosher, J. W. Schumer, J.F. Seely, S.J. Stephanakis, C.J. Szabo, N.R. Pereira, and L.T. Hudson, 2010 IEEE International Conference on Plasma Science (Norfolk, VA, June 2010), p. 227.

[OTT10] "Voltage and Ion Current Measurements for an Ion Diode Driven by Mercury in Positive Polarity with Layered MITL Flow," P.F. Ottinger, R.J. Allen, J.P. Apruzese, D.D. Hinshelwood, S.L. Jackson, D. Murphy, D. Phipps, J.W. Schumer, B.V. Weber, and F.C. Young. *2010 IEEE International Conference on Plasma Science* (Norfolk, VA, June 2010), p. 385.

[PER10b] "K-Line Spectra of Warm, Dense Plasmas Produced with Intense Pulsed Electron Beams," N.R. Pereira, B.V. Weber, J.P. Apruzese, D. Mosher, J.W. Schumer, J.F. Seely, C.I. Szabo, C.N. Boyer, S.J. Stephanakis, L.T. Hudson, 18th High-Temperature Plasma Diagnostics Conference (Wildwood, NJ, May 2010).

[WEB09] "HEDP Production from Plasma-Filled Rod-Pinch Diodes," B.V. Weber, R.J. Allen, J.P. Apruzese, R.J. Commisso, G. Cooperstein, D.D. Hinshelwood, D. Mosher, D.P. Murphy, P.F. Ottinger, D.G. Phipps, J.W. Schumer, S.J. Stephanakis, and S.B. Swanekamp. *DOE ReNeW HEDLP Workshop* (Rockville, MD, November 15-18, 2009).

[PER09b] "Anomalous fluorescence line intensity in megavoltage bremsstrahlung," N. Pereira, M. Litz, G. Merkel, J. Schumer, J. Seely, J. Carroll, Bull. Am. Phys. Soc. **54** (15), (2009).

[SCH09a] "Basic research towards use of radioisotopes as an energetic material," J.W. Schumer et al., Energetic Materials Intelligence Seminar (invited), Aberdeen Proving Ground, May 2009.

[SCH09b,c] "Potential for Electron-Beam Ionization for Accelerated Decay of Radioisotopes," J.W. Schumer, J.P. Apruzese, B.V. Weber, J.F. Seely, M.S. Litz, G. Merkel, and N. Pereira, 2009 Winter Colloquium on Physics of Quantum Electronics (Snowbird, Utah, January 2009) and Army Research Laboratory Radioisotope Battery Workshop (Adelphi, MD, February 2009).

[WEB08b] "High Energy-Density Plasma Production from Plasma-Filled Rod-Pinch Diodes," J.W. Schumer, B.V. Weber, D. Mosher, and J.P. Apruzese, Bull. Am. Phys. Soc. **53** (5), 89 (2008).

[LIT08] "Investigations toward the possible use of energy from isomeric nuclei," M. Litz, G. Merkel, N. Pereira, J. Carroll, Bull. Am. Phys. Soc. 53 (5), 103 (2008).

[BAL08] "Preliminary Tests of Induced Depletion of ^{108m}Ag Using Bremsstrahlung Radiation," T. Balint, G. Trees, I. Mills, M. Ragan, N. Caldwell, T. Harle, R. Gurney, M. Litz, G. Merkel, N. Pereira, M. Helba, H. Roberts, J. Schumer, S. Karamian, J. Carroll, Bull. Am. Phys. Soc. 53 (3), 2008 (Youngstown, OH).

[SEL08] "Hard X-Ray Inner-Shell Spectra Produced by Intense Picosecond Laser Pulses and Recorded by Cauchois Type Spectrometers," J. Seely, G. Holland, C. Szabo, L. Hudson, A. Henins, P. Audebert, S. Bastini-Ceccotti, and E. Tabakhoff, 21st Intl. Conf. on X-ray and Inner Shell Processes, June 2008.

b) *Consultative and advisory functions to other laboratories and agencies and other DoD laboratories.* Consulted with DTRA program managers and directors in related 6.2 efforts (various times and locations). Continued discussions of current and future research with Jason Aquino & Ed Scholz of SciTor Corporation (who are working in conjunction with Dr. George Ullrich/SAIC) in the collection of information for DASD/Forces Transformation and Resources (Mr. Mark Gunzinger's office) and OSD/Policy with regard to various nuclear technology options (July 2008 – August 2009). Attended Energetic Materials Intelligence Seminar (McLean, VA, May 2008 and Aberdeen Proving Ground, May 2009) and discussed research with interested parties in attendance. Discussed topics of accelerated decay of radioisotopes with colleagues at Youngstown State University (Dr. Jeff Carroll), Max Planck

Institute for Nuclear Physics (Dr. Adriana Palffy), Institute for Defense Analysis (Dr. Jim Silk), and served on Army Research Laboratory review panel for radioisotope batteries.

c) *Transitions.* None.

d) *New discoveries, inventions, or patent disclosures:* None.

e) *Honors/Awards* (not received during this reporting period): Dr. John Apruzese, Fellow of the American Physical Society (APS) and Dr. John Seely, Fellow of the American Physical Society (APS) and Optical Society of America.

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